A roadmap for the detection and characterization of other earths

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A Roadmap for the Detection and Characterization of Other Earths

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Abstract

The European Space Agency and other space agencies such as NASA recognize that the question with regard to life beyond Earth in general, and the associated issue of the existence and study of exoplanets in particular, is of paramount importance for the 21st century. The new Cosmic Vision science plan, Cosmic Vision 2015–2025, which is built around four major themes, has as its first theme: "*What are the conditions for planet formation and the emergence of life?*" This main theme is addressed through further questions:

(1) How do gas and dust give rise to stars and planets?
(2) How will the search for and study of exoplanets eventually lead to the detection of life outside Earth (biomarkers*)?
(3) How did life in the Solar System arise and evolve?

Although ESA has busied itself with these issues since the beginning of the Darwin study in 1996, it has become abundantly clear that, as these topics have evolved, only a very large effort, addressed from the ground and from space with the utilization of different instruments and space missions, can provide the empirical results required for a complete understanding. The good news is that the problems can be addressed and solved within a not-too-distant future. In this short essay, we present the present status of a *roadmap* related to projects that are related to the key long-term goal of understanding and characterizing exoplanets, in particular Earth-like planets. Key Words: Exoplanets—Life in the Universe—Space missions—Biomarkers. Astrobiology 10, 113–119.

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*The term biomarker is used here to mean detectable atmospheric species or set of species whose presence at significant abundance strongly suggests a biological origin.

1. Are We Alone in the Universe?

The European Space Agency's Astronomy Working Group, following analysis of the responses to the first Call for Missions for the Cosmic Vision Plan, has recognized the importance of this objective. It has therefore recommended to ESA the development of the necessary preconditions and technologies for achieving the goal of understanding and characterizing Earth-like exoplanets. To address the issues, a roadmap that takes into account both the near and intermediate future is required; and, in response, ESA has established an Exo-Planet Roadmap Advisory Team (EPRAT).

The time is indeed right for such a team. First, this team can build on the results partly presented in this Habitability Primer by the Terrestrial Exoplanets Science Advisory Team, 2002–2006. Second, an emerging exoplanetary community in Europe is carrying out marvelous science—both with ground-based facilities (in areas such as radial velocity searches, transit photometry, and studies of gravitational microlensing events), and with the recent **Co**nvection, **Ro**tation and planetary **T**ransits (CoRoT) space mission. The formation of the Blue Dot Team in Europe in the last year has provided a community basis for EPRAT to work with. By creating a science and technology roadmap, ESA will have the possibility to be flexible within budget constraints and international collaborations (*e.g.*, to be able to quickly set up collaborations with space missions outside Europe). The advisory team carrying out the formulation of the roadmap will consult with the broader community and not limit itself to European partners only. The advisory team began in the middle of 2008 by issuing a call for *white papers*, to which they received over 25 replies. These white papers are being evaluated, and due consideration will be given to them in the report, which will also solicit input in many different ways (interviews, workshops, etc). The final report, which is anticipated in mid-2010, is expected to cover the intermediary and long-term science goals for the field of exoplanet future research and will include (among other topics) a survey of existing and planned facilities—both ground- and space-based—and the science goals likely to be achieved with these facilities. The EPRAT team will also identify (as well as is possible) the future facilities planned and the relevant technologies that will need to be developed at these facilities to achieve the goals. The team also needs to identify the intermediate milestones that must be met before the longer-term goals can be considered feasible.

An Earth-like planet in the habitable zone (HZ) of a nearby sun-type star will be separated by less than 100 milliarcseconds from the host star, as viewed from our Solar System, and its reflected light will appear 10^6 and 10^{11} times fainter, depending on the wavelength. The technical challenge to studying the spectra of Earth-like exoplanets in their systems' HZs is to develop an instrument with the capability to detect an extremely faint source, located very close to its star some several million times brighter. A simple comparison would be to consider how to detect the faint light from a firefly sitting a few millimeters away from the filament of a bright spotlight. The dynamic range needed to recover faint emission from an exoplanet against the glare of its host star requires techniques not currently available to astronomers. In addition to removing the unwanted photons from the host star, we also need to collect the light (perhaps 1 photon s^{-1} m^{-2} of collecting area) from the exoplanet and analyze its light in a spectrometer to search for spectral signatures of gases, such as oxygen, water, ozone, methane, in its atmosphere. This is a similar spectroscopic technique to atmospheric remote sensing that is carried out from Earth and from downward-looking satellites used to investigate our terrestrial atmosphere and biosphere. These spectral markers will provide evidence of whether an environment benevolent to life exists within the exoplanet's atmosphere and whether there are signs that life processes have modified the composition of its biosphere. It is now clear that such missions are technologically feasible within the Cosmic Vision 2015–2025 program.

Today, almost all the known exoplanets are gas giants or, at the least, very different from terrestrial planets. Within our Solar System, Earth is the only rocky planet that has the very special characteristics required to host and nurture the evolution of life. Although we do not know how rare or common our type of system is, ESA's CoRoT mission is designed to search for terrestrial planets—rocky worlds similar to our own—by detecting planets not too dissimilar to our own that pass in front of their parent stars. It is expected that, within a year, we should have statistically robust samples that will tell us the incidence of rocky planets around other stars. This will then set the scene for a major step forward by providing the first robust quantitative spectral diagnostics of the atmospheres of Earth-like exoplanets.

Since antiquity, the question of whether life exists elsewhere has provoked and challenged our view of the Universe and posed even deeper questions about how life should be defined! A very pertinent question, it has deep philosophical implications and questions the nature of human existence, our origins, and our Cosmic Genesis. Central to this debate is development of an understanding of the conditions that could allow life to arise on other planets. The seemingly simple question we want to answer is

Are we alone in the Universe?

If other civilizations do exist elsewhere, could we make contact with them and exchange knowledge? Such contact could lead to a revolution in the development and furtherance of human knowledge. It could be hoped that such contact would lead to a major step forward in improving our understanding of the Universe, because other technological civilizations would perhaps be expected to be scientifically and technologically more advanced than we are. The preceding arguments are exactly those that motivate the current SETI searches. However, within the context of SETI, we have to ask what is the meaning of *a null result*, that is, how should we interpret the current lack of success in identifying radio signals of alien origin? We are presently unable to conclude whether this is because there are no other technological civilizations out there or whether we have simply not looked for the proper type of signals that they emit. Or might it be the case that most technological civilizations are radio or light silent due to the use of another means of communication or the desire not to announce their presence? The only conclusion would be that we have to search harder. Naturally, all these objections would vanish in the case of a success.

Although life on our Earth has existed for several thousands of millions of years, and our own species for possibly several millions (with a relatively loose definition of what our species is), we have only possessed the capability to send signals to the stars during the last one hundred years. While our radio and TV transmissions may have been leaking out from Earth and into a sphere expanding at the speed of light since the year 1900, we are changing more and more to direct transmissions, narrow beams, or cables (except for communications with vehicles, *e.g.*, planes, boats). Would another civilization behave similarly? We do not know, but the implications could be that the *signals* of an external civilization might only be detectable for a very short period during the evolution of a civilization!

On the other hand, life has existed on the planet Earth since at least the end of the era of massive bombardment shortly after the formation of the Solar System. During this violent epoch in Earth's history, the local environment was probably quite hostile to the development of life. It has been estimated that during part of this epoch Earth was impacted by a body in the 100 km size class every 10^6 years, which raised the temperature of Earth's surface to approximately 1200 K and boiled off at least the upper few hundred meters of any oceans existing at the time. If life did manage to start between these impacts, it is difficult to know whether it survived the subsequent cataclysmic events or had to begin again completely from scratch. What is clear, however, is that a relatively short period after Earth settled down, life established itself very rapidly.

Although the details are still being debated, the emergence of early forms of life leaves an imprint on a planetary atmospheric environment that can potentially still be observed thousands of millions of years later by observers many light-years away. This could allow us to infer the emergence of life on other planets across interstellar distances. Life's modifications to the chemical equilibrium in a planetary atmosphere can be used as a quantitative diagnostic of whether life is ubiquitous within the local universe and perhaps can be used to understand whether life is, in fact, an almost inevitable consequence that follows the formation of a star.

In seeking to answer the question as to whether we are alone, we might consider several related areas, including

- Are there planets around other stars?
- Among these exoplanets, what is the frequency of habitable Earth-like planets?
- Do any of these exoplanets show evidence, through modification of their atmospheric constituents, that biological processes may have already started on their surfaces?
- If alien life does exist, has any of it evolved to technical civilizations that we can contact?

The answer to the first of these questions is already known due to the pioneering European discovery of the planet 51 Peg b in October 1995 by Michel Mayor and Didier Queloz, who used radial velocity observations of stars (Fig. 1). Subsequent studies have shown that the occurrence of planets around other stars appears to be relatively common. This has now moved the subject beyond the domain of speculation, allowing quantitative comparison of the properties of objects in other Solar Systems (comparative planetology). Today, more than 350 exoplanets have been discovered, which range from giant gas planets akin to Jupiter and Saturn to rocky worlds as small as 5 Earth masses.

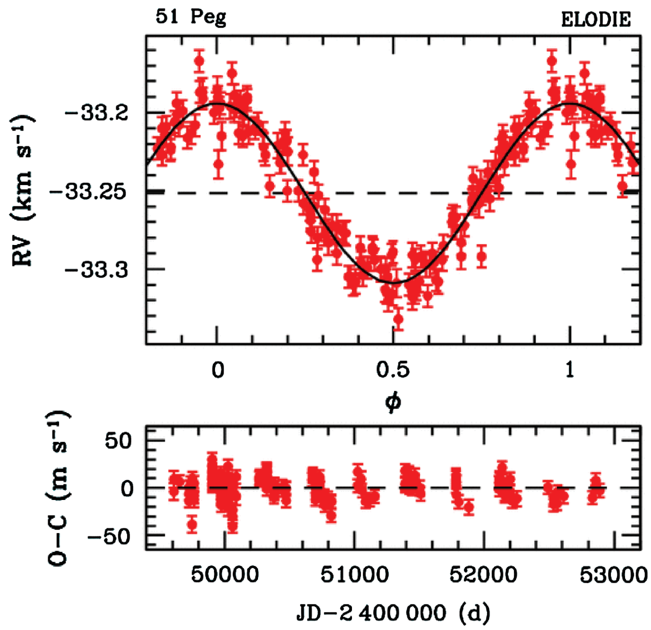

FIG. 1. Discovery of an alien world! The Doppler shift of the solar-type star 51 Peg, as measured by Michel Mayor and Didier Queloz in October 1995, indicating the presence of a giant planet with $M_{\rm pl}.\sin(i) = 0.44\,M_{\rm Jup}$ and a period of 4.2 days corresponding to an orbit of 0.051 AU, a distance to its star that is 7.6 times less than the distance of Mercury from the Sun (Mayor and Queloz, 1995). Color images available online at www.liebertonline.com/ast.

It has not been clear whether the few planets detected that have masses below 10 Earth masses ($M_{\rm Earth}$) are rocky worlds, very small gas giants, or something new and not existing in our Solar System, such as the proposed *ocean planets*. Nevertheless, the recent detection of $>2\,M_{\rm Earth}$ and $>5\,M_{\rm Earth}$ exoplanets in the region of the HZ of the red dwarf Gliese 581 system provides the first clear indication that we are now able to start detecting planets not much larger than Earth and that the planets' location in the HZ of Gliese 581 tells us that this is a system that could potentially nurture the emergence of life. These planets could very well be rocky; and, if that is the case, statistics alone would indicate that a large number of such worlds are in existence.

The quantitative answer to this question is awaiting complete results from space missions in search of exoplanet transits across the disks of nearby stars. CNES/ESA's current CoRoT mission has been operating for more than 2 years (see below) and has just produced a first definitely *rocky* planet (both mass and radius is known for this planet), albeit it is not in the HZ of its star. The NASA Kepler mission has just (spring 2009) begun its scientific work and will explore a larger range of orbital periods.

After these first missions, the road becomes more complex, and the technology required will necessitate further development—probably (and maybe even preferably) in a hand-in-hand process between ground-based and astronomy and space missions. The capability to carry out remote sensing of the atmospheres of Earth-like exoplanets will provide a big leap forward in knowledge, which will generate information about the planets' atmospheric compositions and permit us to make quantitative estimates of the water vapor content that will tell us whether there is liquid water at their surfaces. The presence of liquid water is considered to be a necessary condition for the development of life similar to ours, that is, one based on carbon chemistry in solution in liquid water. The corresponding planets would be called *habitable planets*.

Fortunately, nature has provided a way for us to answer this long before we carry out direct exploration of star systems with astronauts or robotic spacecraft. The crucial test is to measure planets' atmospheric spectra, which will tell us whether *biosignatures of life exist in exoplanetary atmospheres*. The presence of certain gases provides a clear test of the existence of local biological activity—particularly transient species, such as methane or ozone, that are normally destroyed on short timescales by natural processes in atmospheres—their presence in an exoplanet's atmosphere requiring that some process of continuous replenishment occur. For a planet in an HZ (*i.e.,* located at a distance to its star similar to the Earth-Sun distance renormalized by the stellar luminosity), the simultaneous presence of CO_2, H_2O, and O_3, or that of CH_4 and O_3, or N_2O in certain ratios can indicate the presence of life processes.

Biosignatures are the biological imprints of molecular species that are made, in this context, on the atmospheric makeup of an explanatory atmosphere, which cannot be explained by abiotic geological, photophysical, or photochemical effects. For instance, it seems that the simultaneous presence of CO_2, H_2O, and O_3 is a characteristic of photosynthetic activity at the planetary surface. This simultaneous presence is likely to have a biological origin because it requires complex production units. The main (the only?) way to build such units implies an evolution/selection of a biological device. A chloroplast, which is the molecular machinery nature has evolved as a basis unit for photosynthesis on Earth, is a complex assembly, containing $\sim 10^7$ large organic molecules (phospholipids, proteins, and nucleic acid molecules containing ~ 200, ~ 3000, and $\sim 10^7$ atoms, respectively). It is able to store the energy of eight photons before achieving the reduction of a molecular group ($CO_2 + H_2O$) into part of an organic molecule. Storing the energy of even two photons and making it available for a chemical reaction is not readily available by natural or abiotic systems on Earth. Presently, we do not see any process that could do it on an exoplanet at a scale that could modify the whole atmosphere.

The second fortunate point is that many of the gases that can be used as biosignature fingerprints have characteristic spectral bands in the thermal IR (*e.g.,* 6–20 μm) and in the visible to near IR, which can be remotely detected by spectroscopy of the planets.

The detection of signs of life on other planets will arguably be one of the greatest discoveries in the history of mankind!

We will never be quite alone again, and the detection of the signature of extrasolar biological activity would tell us that the Universe may indeed be teeming with life!

2. Brief Overview of Ground-Based Facilities and Space Missions

In this section, we will give a brief overview of the ground-based facilities and space missions that are under implementation, being planned, or under study. This list of facilities will not at this time be exhaustive—that is the task of the EPRAT report in June 2010—but it will give an indication of how the final roadmap/report will look.

2.1. Space missions

CoRoT. The first space mission specifically designed to search for exoplanets similar to the Earth itself was launched in December 2006. This is the French space agency (CNES) mission CoRoT, which was launched with a Soyuz-Fregat rocket and is a small (27 cm aperture) space telescope orbiting in a 900 km high, Sun-synchronous polar orbit around Earth. The method used is the transit method, that is, observing a very large number of stars simultaneously where, assuming a random orientation in space, between 0.5% and tens of percent of the objects (depending on the orbital periods of the transiting planets) will experience an eclipse of a portion of the stellar surface, which will cause a temporary drop (timescale of hours) in the stellar flux. Because of orbital constraints, CoRoT can point inside two 10-degree-wide and diametrically opposed *eyes* on the sky for 150–180 days each.

Thus, a particular sample of stars can be followed with almost no interruptions (duty cycle $> 95\%$) for such a length of time and provide unprecedented light curves. CoRoT uses half its focal plane for following stars of asteroseismological interest. These targets are all bright (6–9 magnitude), few (about 10 per pointing), and provide extremely high photometric accuracy (0.6 parts per million per month). The other half of the focal plane is what is of interest in the context characterization of other Earths. Here, up to 11,600 stars are followed for an equal amount of time and with the same duty cycle. The stars are fainter (11–16.5 magnitude), and the photometric accuracy is of course less, varying between 10^{-4} and 10^{-5} per hour depending on the stellar brightness. The mission is specifically designed to search for transiting super Earths (1–2 Earth radii) in short-period orbits (<15–20 days, though larger planetary radii are detectable up to periods of ~ 50 days). During almost 900 days in space, CoRoT has found a total of seven exoplanets that have been confirmed. Another eight candidates appear likely to be confirmed as planets, and more than 100 further candidates are being followed up but are in a very early stage of the process. Most of the latter will be background eclipsing or spectroscopic binaries. Note that this is from the first 560 days of data that have been reduced in the data pipeline so far.

The release of the news of the achievement of what could be termed the design goal of CoRoT—that is, to detect and characterize a so-called *super Earth*—was made in February 2009. After more than 1 year of follow-up observations, using every available asset, including the Very Large Telescope at ESO Chile and the NASA Spitzer spacecraft, we have demonstrated that the star CoRoT-7 (G9-K0 spectral type) is orbited by several planets: 7b is of terrestrial type with a radius of about 1.6 times the Earth, a mass of about 5–7 Earth masses, and an orbital period of 0.85 days (distance from the star is about 4.5 stellar radii). This planet is thus *rocky* in the same way that Earth (and Venus and Mercury) is, with an average density between 5.5 and 6 g cm^{-3}. This is the first observation of such an object outside the Solar System. The material already existing from CoRoT has much more to deliver, particularly with regard to the fainter magnitudes and smaller transiting signatures. CoRoT will hopefully continue to collect data for several more years, and it is conceivable that at the end of the mission up to 100,000 light curves of very high quality and long duration (70–150 days) will exist.

Kepler. CoRoT is being followed almost immediately by NASA's Kepler mission, which was launched in March 2009. Kepler has a larger telescope (95 cm) and will be placed in a *drift-away* orbit; it does not suffer the time constraints that CoRoT has. Rather, Kepler can remain pointed toward the same point in the sky for years. Kepler will observe a region in Cygnus for 3–4 years and will thus have the potential to detect small long-period planets. With a significantly larger field of view, Kepler will follow about 100,000 stars and at least double the amount of data from CoRoT, as well as increase the orbital periods.

Together, CoRoT and Kepler, with their associated follow-up programs, will provide the first estimate of the prevalence of terrestrial planets. Although it is unlikely that any of these missions will be able to provide an estimate for such planets in habitable orbits around early G-type stars (orbital periods of order 1 year), the detection of potentially habitable planets (with orbital periods below a few months) around fainter solar-type stars is quite possible.

Herschel. The world's largest space telescope, Herschel, with its 3.5 m mirror, was launched in May 2009 by ESA and will begin regular scientific observations by the middle of this year. While primarily a submillimeter telescope that is intended to clarify issues in star formation, as well as observe the earliest galaxies, it will also do observations that have direct relevance for the exploration of exoplanetary systems. Here, we only mention a few of these projects, which are already approved as guaranteed time observations. Of course, the study of star-forming disks is central and will provide much-needed information about the chemistry of such objects as well as their time evolution. Even more important is the study of debris disks. These objects are believed to result from collisions between planetesimals that remain after the accretion process.

TESS. The Transiting Exoplanet Survey Satellite, called TESS, is a planet-searching satellite planned by scientists from MIT, the Harvard-Smithsonian Center for Astrophysics, and NASA Ames. It is one of six proposed spacecraft concepts NASA has chosen for further study as part of its Small Explorer satellite program. The proposed satellite, TESS, would use a set of six wide-angle cameras with large, high-resolution electronic detectors (CCDs) to provide an all-sky survey of transiting planets around the closest and brightest stars. The capabilities of the proposed spacecraft are such that it could discover hundreds of *super Earth* planets, which would range in diameter from 1 to 2 times that of Earth, orbiting other stars.

The advantage of this project is that it could do an all-sky survey and utilize relatively bright—and thus nearby—host stars. Any planet found could then be a very good candidate for future (spectroscopic) follow-up projects, for example, the James Webb Space Telescope.

JWST. The James Webb Space Telescope (JWST) is a large infrared telescope with a 6.5-meter primary mirror. JWST is scheduled to launch in 2014. One of the key scientific objectives of this mission will be to study exoplanets. Originally conceived to study the formation of stars and such planets, it has been realized—mainly as a consequence of the work of other space missions like Spitzer and the Hubble Space Telescope—that JWST will make a formidable contribution to the study of exoplanetary atmospheres. It is even a possibility that, if transiting super Earths orbit nearby red dwarf stars, spectra that demonstrate their atmospheric detail—including biomarkers—could be obtained. It must be pointed out, however, that potential targets are relatively few in number.

Another intriguing option would be to supplant JWST with a free-flying and separate occulting spacecraft (a large "star shade") that would fly several tens of thousands of kilometers away from JWST. This could be used to diminish the light from a solar-type target star to a degree where an image of an accompanying Earth-sized planet would be detectable. Whether this is feasible remains, however, to be seen.

SPICA. The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a proposed Japanese mission with a large (3 m class) infrared telescope. In a possible collaboration with the European Space Agency's Cosmic Vision program, it could be equipped with a coronograph to facilitate investigations of (young) exoplanetary systems. One focus of the mission would be detailed (at high spatial resolution) studies of the star- and planet-forming process. SPICA will launch after 2015.

PLATO. Planetary Transits and Oscillations of Stars (PLATO) is a proposed medium-sized Cosmic Vision mission. It will search for, and observe, exoplanetary transits. PLATO will take over in those areas CoRoT and Kepler will have pioneered. The mission will allow, for the first time, observation of stars that are bright enough for asteroseismological signatures to be observed. This will facilitate determination of the stellar parameters with an unprecedented accuracy; thus the planetary parameters will also be known with a significant increase in precision. The measurement of diameters to 1% or 2%, and planet ages to better than 300 million years are some of the goals. PLATO will need a very wide field to allow enough brightness (magnitude 8–11) to be continuously observed for several years. This will be accomplished with the use of a number (15–30 depending on the individual aperture) of separate short-focus telescopes pointed in the same direction on the sky (this will also provide redundancy and have measurements made in separate colors). Each telescope will have its own detectors, and the data will be added together before transmission to Earth. The best asteroseismological measurements will be done on more than 20,000 stars (photometric precision of 27 ppm), while transits of planets the size of Earth or smaller can be observed in a total of more than 300,000 stars. If selected, the mission could be launched in 2017.

Spectroscopic mission. One of the most important recent advances is the detection of exoplanetary spectra from two space missions (Spitzer and the Hubble Space Telescope) as well as from the ground in at least two instances. It has only been a success in the case of a very few "hot Jupiters" and with a spectral resolution of ~ 5. Nevertheless, the results are important, and the promise of success in many, more varied instances is exciting. The transit of exoplanets can be utilized to isolate a planetary signal. This is accomplished by taking a photometric measurement of a planet and its host star while the planet is in transit. Later, another measurement is made when the star is occulting the planet. By subtracting the first signal from the second, the desired planetary signal is attained. Since the planetary signal is extremely faint compared to the stellar one, such measurements demand a very high photometric stability over the timescales in question. It has been shown, however, that if this stability can be increased by a factor of 3–10 or higher, then the available number of targets can be increased significantly. It is even possible that, in some cases, the method could be extended to so called *super Earths,* that is, bodies with radii 1–2 times that of our own world. For stars somewhat fainter than the Sun, it also becomes possible to increase the spectral resolution. Because of this enticing case, studies of dedicated space missions, based on passively cooled 1 m telescopes, have been initiated by a number of entities, including ESA. If—and this is a large if—suitable targets occur within the immediate vicinity of Earth, it may be possible even to address the issue of *habitability.*

SIM-Lite. SIM-lite is a NASA project that could fly in 2020. It consists of a white-light interferometer with a small aperture that could measure astrometric signatures of less than 0.6 microarcseconds for nearby stars. This would allow seeing the deflection in the plane of the sky caused by any accompanying Earth-sized planet for about the 80 closest solar-type stars.

2.2. Ground-based facilities

Second-generation instruments for existing facilities. Several large instruments are being planned for large telescopes currently in use. Given the importance of exoplanetary research, it is not surprising that many of these telescopes have been allocated (sometimes exclusively) for work in this area. The advent of extremely large telescopes (30 m class) will very likely allow that some of today's giants, in the 8 m class, which are currently busy investigating a great variety of different topics, will be dedicated—with appropriate instrumentation—to exoplanetology. Specifically, the next generation of ultrahigh-precision radial velocity machines can, on a dedicated 8 m telescope, take the precision currently available on telescopes like the ESO 3.6 m + HARPS combination (0.5–1 m s^{-1}) and improve it by a factor of 10. Dedicated telescopes are required, since the activity in the target stars demands more-or-less continuous coverage of the whole phase of the orbital revolution of the planetary candidate and, in the case of, for example, super Earths, many periods. Nevertheless, dedicated telescopes will carry the current radial velocity studies into a new domain of exoplanet masses.

Microlensing. Several surveys of microlensing events are currently ongoing and have been successful in a few cases where rather small planets appear to have been detected orbiting very distant stars. The method appears to have significant capability as the technology evolves.

Very large telescopes (30–50 m class). Several large facilities are being planned for the near future. Based on adaptive optics and segmented telescopes, examples are the Thirty Meter Telescope, with (naturally) 30 m effective aperture, in the US, and the 42 m European Extremely Large Telescope in (naturally) Europe. Operating from the UV to the IR, scientific topics addressed by these large machines include star and planet formation, the development of the early Universe, the history of the galaxies that permeate the void, and—one is tempted to say, of course—the study of exoplanets. The characterization of exoplanets would take a giant leap forward since the direct observation of the reflected light from mature large (Neptune- and Jupiter-sized) exoplanets becomes possible. With regard to young, forming planets, it will be possible to trace the early evolution of such objects in clusters and, therefore, understand the initial mass function of such objects.

3. The Far Future

The above-mentioned programs—some of which are flying or will surely fly due to the stage of their development—will take us to about 2020. It is probably also going to lead to the detection of planets the size of our own—also in what is usually called the HZ. This will very likely be accomplished for planets of nearby stars as well as those of stars in more distant stellar populations. We will then have a good idea as to how prevalent different classes of planets are, as well as a better understanding of how planets of different types form. So what is next? If Earth-like planets are common, it is highly likely that some will be found within 10–30 pc. These objects will then be prime targets for dedicated and detailed studies in an effort to try to ascertain their capacity to host life or whether they already host life. This calls for a completely different class of instruments than those described above. The interferometers of the Terrestrial Planet Finder (TPF-I) (NASA) and Darwin (ESA) have been thoroughly studied during the last decade, as has the coronagraphic system TPF-C (also NASA), and they are believed to be technically feasible after a significant development program. Currently, occulting systems are under study in the US that are similar in principle to the coronagraphs mentioned above, but the occulting disk will be on a separate spacecraft flying very far (thousands of kilometers away) from the telescope. To be successful, this will also require at least a 4 m diameter telescope, and the project thus belongs in the same class as the interferometers and coronagraphs.

It remains to be decided which, if any, of these systems will be selected. In either case, the scientific objective of determining whether we are alone in the Universe remains one of the highest priorities of this century.

Abbreviations

CoRoT, Convection, Rotation and Planetary Transits; EPRAT, the Exo-Planet Roadmap Advisory Team; HZ, habitable zone; JWST, the James Webb Space Telescope; PLATO, Planetary Transits and Oscillations of Stars; SPICA, Space

Infrared Telescope for Cosmology and Astrophysics; TESS, Transiting Exoplanet Survey Satellite.

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